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Compositional Effects on Electromechanical Degradation of RAINBOW Actuators

David E. Dausch and Stephanie A. Wise
Langley Research Center, Hampton, Virginia

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Langley Research Center, Hampton, Virginia

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Langley Research Center
Hampton, Virginia 23681-2199

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Abstract

The effect of ceramic composition on the electromechanical displacement degradation of RAINBOW (Reduced and Internally Biased Oxide Wafer) actuators was investigated. RAINBOWs were fabricated from commercially available PZT-5H and PZT-5A piezoelectric disks as well as from tape cast PLZT piezoelectric 7/65/35 and electrostrictive 9/65/35 compositions. Displacement properties were measured at low electric fields (10 to 13 kV/cm) under loads of 0 to 500 g, and displacement degradation as a function of time was observed over 10^7 cycles. The PZT-5A and PLZT 9/65/35 compositions exhibited minimal decrease in displacement when load was applied. Furthermore, these compositions retained approximately 65 percent of their initial displacement after 10^7 cycles under a load of 300 g. PZT-5H and PLZT 7/65/35 degraded completely under these conditions.

Introduction

High-displacement RAINBOW (Reduced and Internally Biased Oxide Wafer) actuators are receiving increased attention for applications requiring high strain such as noise cancellation, optical positioning, active structural control, and sonar (refs. 1 through 3). These devices are capable of producing unimorph-type bending with single element displacements greater than 1 mm under moderate loads (ref. 3). RAINBOWs are fabricated by chemically reducing, or selectively removing oxygen from, one side of a conventional high-lead-containing piezoelectric or electrostrictive ceramic disk such as PZT (lead zirconate titanate). This process transforms the ceramic into a monolithic domed structure containing a highly metallic layer and a piezoelectric oxide layer. When activated by an electric field, the stress-biased wafer exhibits amplified axial displacements. One target application for RAINBOW devices is a solid-state actuating mechanism to replace mechanical motors for optical positioning in space-borne spectrometers (ref. 4). Such an application would require repeatable displacement properties while operating below 1 Hz for 10 million cycles under moderate applied load.

The use of RAINBOWs in applications that require long device lifetimes necessitates assessment of the long-term reliability of these materials. Ferroelectric polarization fatigue in piezoelectric and electrostrictive RAINBOWs has been investigated and compared with fatigue in conventional ceramics over 10^8 cycles (ref. 5). Ferroelectric fatigue is the degradation of the nonlinear electrical properties caused by repeated cycling at high electric fields (i.e., greater than 20 kV/cm). Typical actuator devices, however, would not be driven by such large fields. In order to characterize these materials under conditions which better emulate actuator applications, the electromechanical displacement properties of RAINBOWs activated by low ac (alternating current) fields were observed. The objective of this investigation was to examine the effects of the starting ceramic composition on the electromechanical displacement degradation of these materials. RAINBOWs were fabricated from commercially available PZT wafers as well as tape cast PLZT (lanthanum-modified PZT) ceramics. Actuator displacements were measured under static loads of 0 to 500 g, and degradation in the displacement properties over time, or displacement fatigue, was characterized for up to 10^7 cycles.

Experimental Procedure

PLZT piezoelectric 7/65/35 (65/35 Zr/Ti ratio with 7 percent La dopant by weight) and PLZT electrostrictive 9/65/35 ceramics were produced by tape casting for RAINBOW fabrication. Powder for tape casting was synthesized at 900°C from mixed oxides of lead, lanthanum, zirconium, and titanium. Ball-milled powder was then combined with a resin solution (Ferro UN1866 resin) and cast into thin sheets (approximately 500 μm when dried) on a Du Pont Teflon surface. Circular disks were punched from the dried tapes and sintered at 1275°C on $PbZrO_3$ powder beds. Use of the beds provided a sintering atmosphere which was rich in PbO to minimize PbO loss from the ceramics. The fired ceramics were 300 to 360 μm (12 to 14 mils) in thickness and 22.2 mm (7/8 in.) in diameter. RAINBOWs were also fabricated from commercially available PZT-5A and PZT-5H piezoelectric disks. These disks were 25.4 mm (1 in.) in diameter and 380 μm (15 mils) in thickness. The piezoelectric and electrostrictive ceramics were chemically reduced by placing the oxide ceramic disks on graphite blocks in a furnace at 975°C for approximately 1 hour to form the oxide and metal layered structure. The remaining oxide layer comprised approximately 50 to 60 percent of the total thickness of each RAINBOW. After quenching the RAINBOWs to room temperature, silver epoxy electrodes were applied to both surfaces. RAINBOWs with electrodes were poled at room temperature with a dc (direct current) bias of 400 to 500 V.

Electromechanical degradation was measured by applying ac electric fields of ±6.5 kV/cm (±16.5 V/mil) to the commercial piezoelectric compositions, ±5 kV/cm

(±12.5 V/mil) to the piezoelectric PLZT 7/65/35 composition, and 10 kV/cm (25 V/mil) unipolar (i.e., 0 to 10 kV/cm) to the 9/65/35 electrostrictors. These low electric fields were chosen to ensure that each composition produced displacements in their respective linear ranges. Electrostrictors were driven with unipolar voltage since both positive and negative voltages produced equal displacements in the same direction. Because the chemically reduced layers had low electrical resistance (less than 1 Ω), electric fields were calculated by assuming that the voltage was dropped only across the oxide layers. Electromechanical displacements under loads of 0 to 500 g were measured at a frequency of 1 Hz. Displacements were sensed with linear variable displacement transducers (LVDT), and static point loads were applied by placing known weights on the LVDT rod which rested on the top surface of the RAINBOW. Displacement fatigue was measured at a frequency of 20 Hz for 10^7 cycles under loads of both 0 and 300 g. The fatigued samples were repoled, and displacements were immediately measured again at 20 Hz.

Results

Effect of Static Load on Displacement

Displacement (*D*) values under loads of 0 and 500 g as well as the percentage change in displacement with applied load are listed in table 1. These values represent an average of five samples per composition. Higher free (no load) displacement was observed for the commercial piezoelectric compositions than for PLZT 7/65/35. For PZT-5A, displacement decreased by only 2 percent when a load of 500 g was applied as compared with a 20- and 34-percent decrease for the two other piezoelectrics. Electrostrictive PLZT 9/65/35 exhibited the highest overall displacement and best load-bearing capability of all the RAINBOW compositions tested.

The normalized displacement properties of RAINBOWs under loads of 0 to 500 g are shown in figure 1 and indicate the relative dependence of displacement on applied load for each composition. As shown, piezoelectric PZT-5H and PLZT 7/65/35 exhibited

Table 1. Average Displacements (*D*) of Unloaded and Loaded RAINBOWs

RAINBOW composition	D_{0g}, µm	D_{500g}, µm	$\Delta D_{0\text{-}500g}$, percent
PZT-5H[a]	83	66	−20
PZT-5A[a]	88	86	−2
PLZT 7/65/35[b]	55	36	−34
PLZT 9/65/35[c]	116	117	+1

[a]Peak-to-peak displacements at ±6.5 kV/cm and 1 Hz.
[b]Peak-to-peak displacements at ±5 kV/cm and 1 Hz.
[c]Peak-to-peak displacements at 10 kV/cm (unipolar) and 1 Hz.

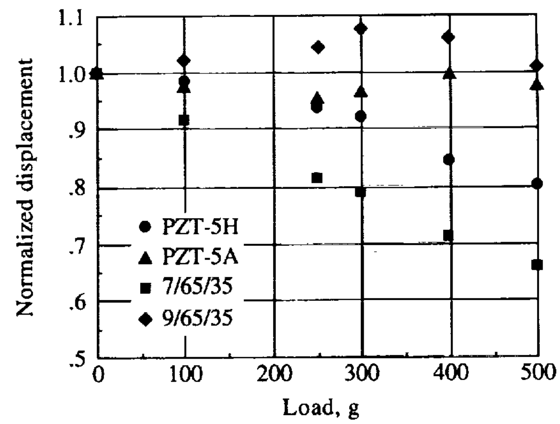

Figure 1. Change in displacement with various static loads. Field levels were 10 kV/cm unipolar for electrostrictive 9/65/35, ±5 kV/cm for piezoelectric 7/65/35, and ±6.5 kV/cm for commercial piezoelectric compositions at 1 Hz.

continuously decreasing displacements with increasing load. PZT-5A displacement values under all test loads were no more than 5 percent lower than the initial free displacement for this composition. The displacement of the electrostrictive composition actually increased by as much as 8 percent under a load of 300 g compared with the properties under no load.

Low-Field Displacement Fatigue

Degradation in the displacement properties as a function of time was investigated for RAINBOW actuators to determine the characteristics of these devices over long lifetimes. Table 2 is a summary of the displacement fatigue characteristics including fraction of initial displacement remaining after 10^7 cycles (fatigued) and fraction of initial displacement recovered after repoling under loads of 0 and 300 g. Displacement fatigue is shown for PZT-5H, PZT-5A, PLZT 7/65/35, and PLZT 9/65/35 RAINBOWs in figures 2, 3, 4, and 5, respectively.

Table 2. Fractions of Initial Displacement for Unloaded and Loaded RAINBOWs

[Voltage conditions same as in table 1 except at 20 Hz; fatigued data obtained after 10^7 cycles unless otherwise noted]

RAINBOW composition	No load		Load of 300 g	
	Fatigued	Repoled	Fatigued	Repoled
PZT-5H	0.91	1.03	[a]0.06	0.83
PZT-5A	0.92	1.00	0.63	0.94
PLZT 7/65/35	0.78	1.01	[b]0.05	0.05
PLZT 9/65/35	0.80	0.81	0.65	0.63

[a]After 2×10^4 cycles.
[b]After 2×10^3 cycles.

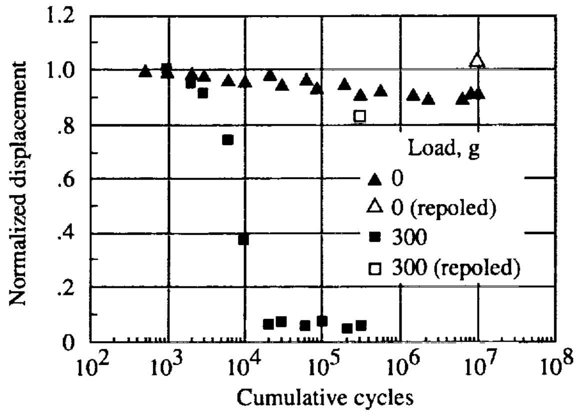

Figure 2. Displacement fatigue of PZT-5H RAINBOWs with applied loads of 0 and 300 g measured at ±6.5 kV/cm and 20 Hz.

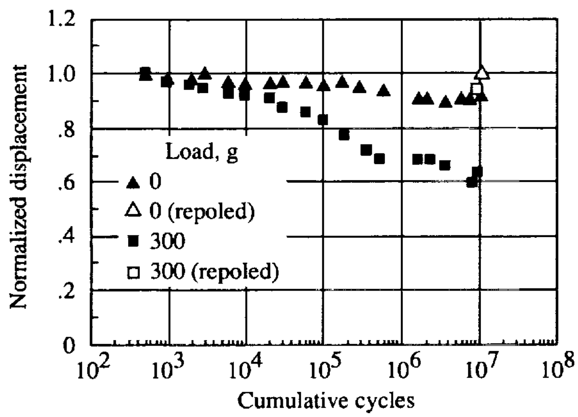

Figure 3. Displacement fatigue of PZT-5A RAINBOWs with applied loads of 0 and 300 g measured at ±6.5 kV/cm and 20 Hz.

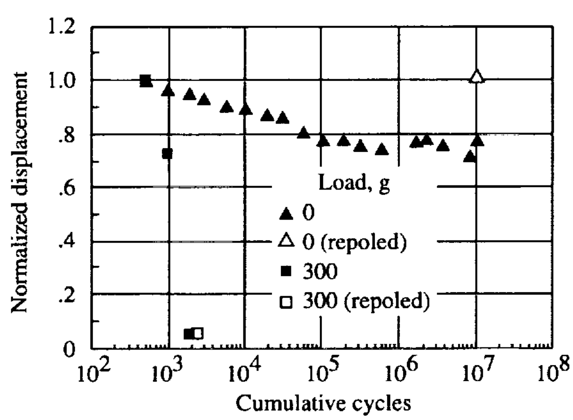

Figure 4. Displacement fatigue of PLZT 7/65/35 RAINBOWs with applied loads of 0 and 300 g measured at ±5 kV/cm and 20 Hz.

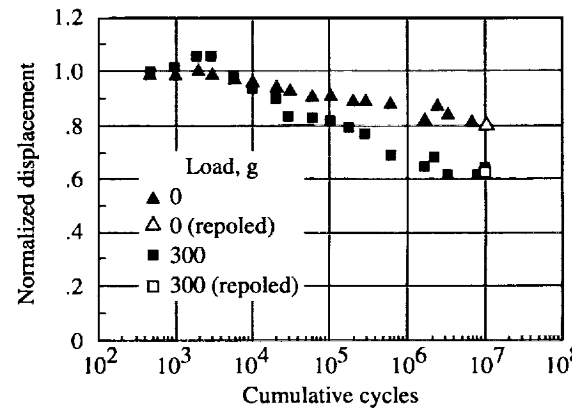

Figure 5. Displacement fatigue of PLZT 9/65/35 RAINBOWs with applied loads of 0 and 300 g measured at 10 kV/cm unipolar and 20 Hz.

The commercial piezoelectric compositions provided the most resistance to displacement fatigue over 10^7 cycles with no load. A displacement degradation of less than 10 percent was observed. However, PZT-5A with its greater load-bearing capability fatigued much less than PZT-5H with an applied load of 300 g. PZT-5H was completely fatigued, that is, 94 percent loss in displacement, after 2×10^4 cycles. When repoled after the fatigue measurements, the original free displacement properties were completely restored for both compositions, whereas 83 to 94 percent of the initial displacement was recovered when repoled under a load of 300 g. This finding reveals that the properties of these materials can be replenished by periodically applying a dc bias (repoling) to the samples during their lifetimes. It is unknown how many dc bias applications can be successfully employed. Consequently, for applications where a load must be considered, the PZT-5A composition would be the most desirable.

Both PLZT 7/65/35 and 9/65/35 RAINBOWs exhibited approximately 20 percent displacement fatigue when no load was applied. The initial higher displacement obtained prior to the fatigue test for the piezoelectric 7/65/35 RAINBOW was recovered by repoling; however, the properties of the electrostrictive 9/65/35 composition were unaffected by repoling. Superior load-bearing capability was evident in the 9/65/35 composition, as 7/65/35 completely fatigued after only 2×10^3 cycles and 9/65/35 retained 65 percent of its original displacement after 10^7 cycles. The initial displacements could not be recovered for either of these compositions when repoled after the fatigue measurement under a load of 300 g.

As shown, composition of the starting ceramic has a large effect on the lifetime and reliability of RAINBOW actuators. Because most applications would require some load-bearing capability, PZT-5A and PLZT 9/65/35 would be the most useful of the four compositions investigated. These compositions continued to retain greater than 60 percent of their initial displacements after 10^7 cycles under applied load. PZT-5A could retain on the order of 90 percent of its initial displacement values with periodically applied dc bias. For an optical positioning mechanism operating at 0.25 Hz, a lifetime of 10^7 cycles for PZT-5A or PLZT 9/65/35 would be equivalent to greater than 11 000 hours of continuous operation. In contrast, PZT-5H and PLZT 7/65/35 under applied load would function continuously for only 22 (2×10^4 cycles) or 2 (2×10^3 cycles) hours, respectively, without periodic repoling.

Summary of Results

Electromechanical degradation was investigated for PZT-based RAINBOW actuators fabricated from piezoelectric PZT-5H, PZT-5A, and PLZT 7/65/35 as well as electrostrictive PLZT 9/65/35 ceramics. Composition had a significant effect on the electromechanical properties. Specific results were as follows:

1. The PZT-5A and PLZT 9/65/35 compositions provided the greatest load-bearing capability. Minimal decrease in displacement was observed for these compositions with static loads of 500 g, whereas the PZT-5H and PLZT 7/65/35 compositions exhibited decreases of 20 and 34 percent, respectively.

2. The commercial PZT piezoelectric compositions exhibited the lowest decrease in free displacement over 10^7 cycles (i.e., less than 10 percent), whereas the properties of the tape cast PLZT RAINBOWs diminished by approximately 20 percent. Repoling the three piezoelectric RAINBOWs after the no load fatigue measurement restored displacements to their initial values. Electrostrictive displacement properties could not be restored by repoling.

3. The PZT-5A and PLZT 9/65/35 compositions retained approximately 65 percent of their initial displacement when a load of 300 g was applied for 10^7 cycles. Additionally, PZT-5A displacement was restored to 94 percent of the initial value by repoling after the fatigue measurement. The PZT-5H and PLZT 7/65/35 compositions possessed relatively short lifetimes (less than 2×10^4 cycles) with applied load. These results indicated that for optical positioning applications, the PZT-5A and PLZT 9/65/35 compositions would provide greater electromechanical repeatability.

NASA Langley Research Center
Hampton, VA 23681-2199
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